# NAVAL POSTGRADUATE SCHOOL
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# THESIS

**SATISFYING WAR-TIME FUEL REQUIREMENTS WITH A MINIMAL TANKER COMPLEMENT**

by

Kent A. Michaelis

September, 1997

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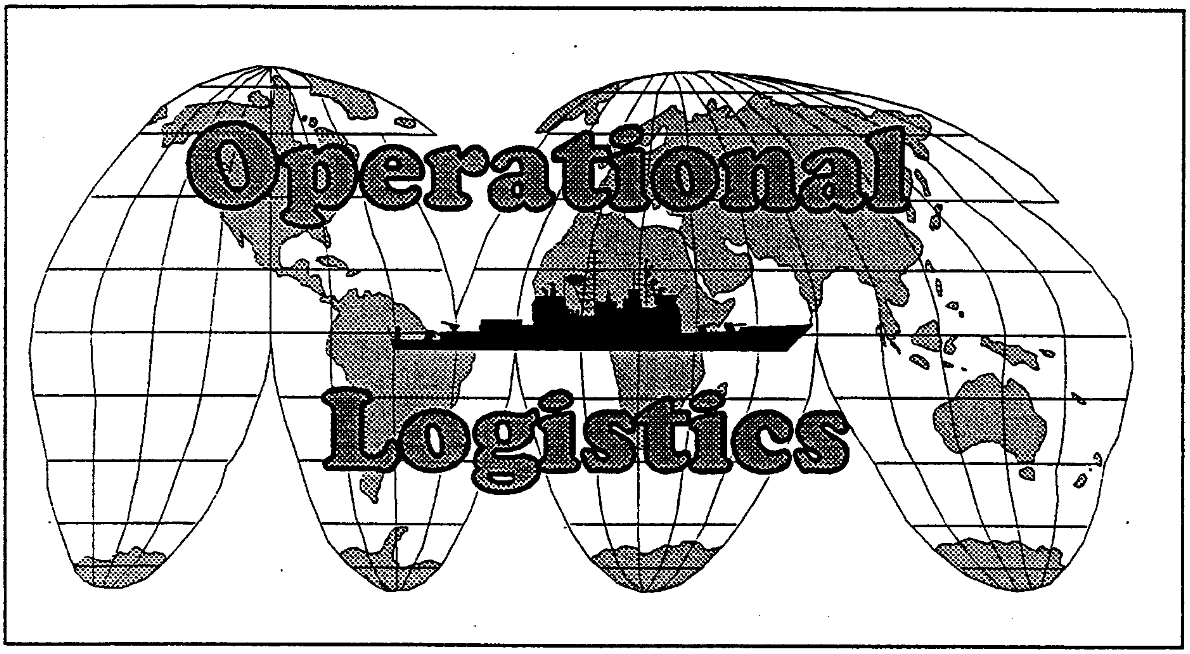
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# SATISFYING WAR-TIME FUEL REQUIREMENTS WITH A MINIMAL TANKER COMPLEMENT

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## ABSTRACT

The United States Transportation Command (USTC) must ensure that sufficient assets are available to transport the war-time requirements of Petroleum, Oil and Lubrication (POL) for the military. To be confident that sufficient assets exist to transport POL, USTC must know the number of tankers required. The Mobility Division of the Logistics Directorate of the Joint Staff (J4-MOB) uses a simulation model, the Model for Intertheater Deployment by Air and Sea (MIDAS), to determine the required number of tankers. MIDAS' use is problematic since many runs may be needed, each run is manpower-intensive, and results do not necessarily define the minimum number of tankers. This thesis couples a schedule generator and an integer linear programming (ILP) model to determine the minimum number of tankers to satisfy war-time POL requirements. Solving a realistic scenario provided by J4-MOB (spanning 75 days with 92 available tankers), the ILP selects 19 tankers, one-third the number initially chosen by MIDAS. Using the ILP's recommended schedules, MIDAS confirms the ILP's solution. These results show that the schedule generator and the ILP can assist J4-MOB.

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## EXECUTIVE SUMMARY

The Department of Defense (DoD), under the authority and direction of DoD Directive 5100.1, provides military forces needed to deter war and protect the security of the United States. To support the forces, DoD must maintain adequate supplies, key among them petroleum, oil and lubrication (POL) products. War-time requirements for surge (initial buildup) and sustainment (continuing requirements) may exceed the capacity of DoD POL assets. The shortfall is alleviated by the use of commercial US-flagged vessels.

The Secretary of Transportation (SecTrans) is responsible for making sufficient POL lift capacity available, and the Maritime Administration (MARAD) provides the oversight of this responsibility. To ensure sufficient lift capacity remains in the US-flagged vessel inventory, MARAD must authorize any re-flagging request from the vessel's owner. Prior to approval, MARAD receives a recommendation from DoD on whether the US-flagged vessel's re-flagging would impair POL lift capacity.

In 1991, the Mobility Requirements Study (MRS) generated a tanker study which included a recommendation for tanker fleet composition. Prior to the release of the tanker study's results, the MRS Bottom Up Review - Update (MRS BURU) study modified underlying assumptions rendering the results of the MRS no longer germane. There is no published quantifiable number of tankers that defines minimum fleet size or capacity required to meet war-time commitments.

In 1997, the Mobility Division of the Logistics Directorate of the Joint Staff (J4-MOB) conducted a tanker study using a simulation program, the Model for Intratheater Deployment by Air and Sea (MIDAS). However, the simulation model requires intelligent, user-influenced information prior to running the model. This information consists of initial starting conditions that influence the outcome (where and when to onload fuel, how much fuel to onload, etc.). Knowledgeable users determine these conditions, without quantitative information on how these conditions may adversely affect the final outcome.

This thesis develops a schedule generator that generates all, feasible tanker schedules. The schedules are provided as input to an integer linear programming (ILP) model that determines a collection of schedules that meet the war-time fuel requirements

with a minimum complement of tankers. For an unclassified but realistic scenario provided by J4-MOB (spanning 75 days, sixteen onload ports, seven offload ports, two fuel types, and 92 available tankers), the schedule generator and the ILP provide significantly better results than those initially provided by MIDAS. To satisfy the problem's fuel requirements, the ILP requires only 19 tankers; MIDAS initially required 60. However, utilizing the schedules selected by the ILP, MIDAS also solves the problem using only 19 tankers. The results are achieved in less than seven hours on an IBM RS/6000 Model 590 computer, and the results demonstrate that the schedule generator and the ILP can assist J4-MOB.

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# I. INTRODUCTION

This thesis provides a methodology for determining the minimum number of petroleum, oil and lubrication (POL) tankers required for a given war scenario. (Appendix A contains a list of applicable acronyms.) The methodology separates into two parts: For a given war-time scenario, a schedule generator uses information about tankers, fuel requirements, and ports of embarkation and debarkation, to create a set of feasible ship schedules; an integer linear program (ILP) then determines a subset of those ship schedules that satisfies fuel requirements with the fewest number of tankers.

## A. BACKGROUND

The Department of Defense (DoD), under the authority and direction of DoD Directive 5100.1, provides military forces needed to deter war and protect the security of the United States [DoD, 1997(a)]. To support the forces, DoD ensures there exist sufficient quantities of supplies, key among them, POL products. POL tankers (Figure 1) transport the vast quantities of this bulky, heavy product.

During war time, POL requirements for surge (initial delivery and buildup) and sustainment (long-term continuing requirements) exceed the transport capability of tankers owned by DoD. DoD relies on the Department of Transportation (DoT) to provide additional POL tankers. The Shipping Act of 1916, Sections 9 and 37 (as amended through the $102^{nd}$ Congress) provides the legislative means. The DoT has relied on the Shipping Act's resulting availability of commercial, United States' flagged POL tankers during several wars [Congressional Budget Office, 1997, p. xi].

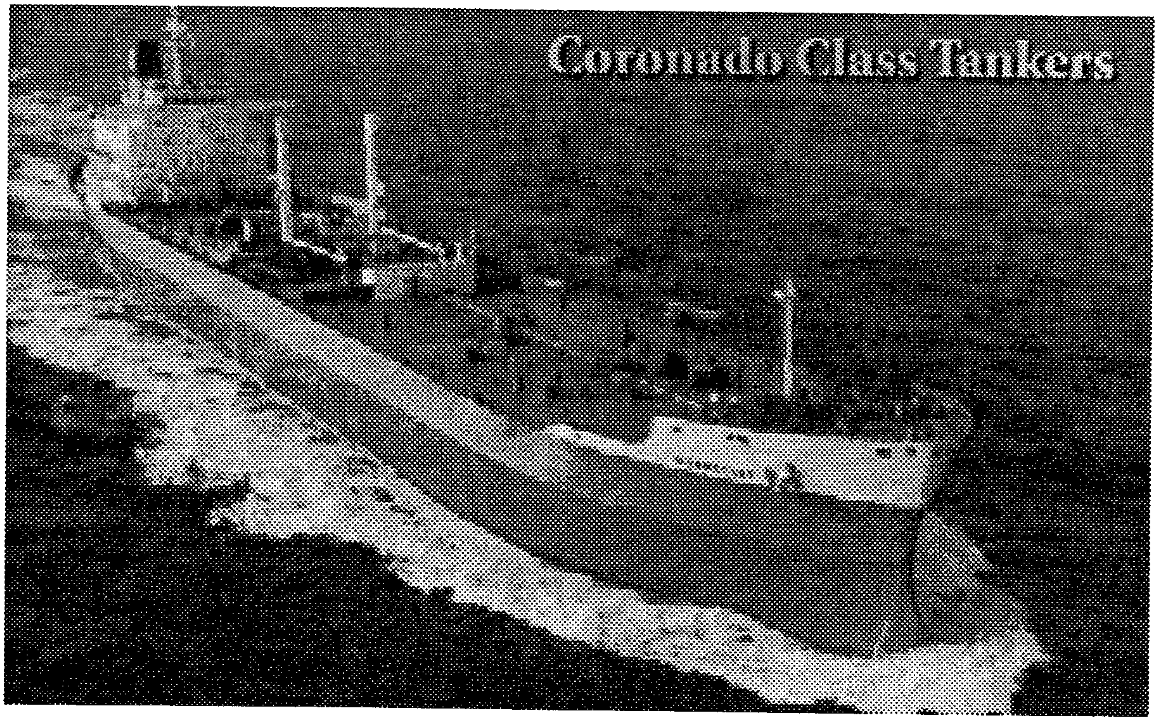


**Figure 1** - One of over 50 US-flagged POL tankers, ***SS MORMACSKY*** is available during war-time to transport bulk POL products. ***SS MORMACSKY*** (a medium-sized tanker) has a draft of 35 feet, a cruising speed of 16 knots, and carries 283,000 barrels of petroleum products [National Steel and Shipbuilding Company (NASSCO), 1997(a)].

### 1. Government Relationships

The Secretary of Transportation (SecTrans) is responsible for ensuring commercial POL tankers are available for war-time requirements, and his conduit for executing this responsibility is the Maritime Administration (MARAD). MARAD approves the re-flagging of a US-flagged vessel to a foreign flag provided it is not "militarily useful," and thereby ensures that national assets remain available. MARAD is described as:

> The Maritime Administration (MARAD) is responsible for insuring that merchant shipping is available in times of war or national emergency. MARAD administers programs to meet sealift requirements determined by the Department of Defense (DoD) and conducts related national security activities.
>
> The Agency maintains inactive, Government-owned vessels in the National Defense Reserve Fleet (NDRF) and its Ready Reserve Force (RRF) component. The RRF was created to maintain a surge shipping and resupply capability available on short notice to support deployment of a multidivision force. [MARAD, 1997]

### 2. Reflagging Process

The request for re-flagging originates with the vessel's owner. The request goes to MARAD, and is forwarded to the DoD for endorsement. United States Transportation Command (USTC) is the DoD component responsible for managing transportation assets. USTC ascertains the military value of the vessel and coordinates the official DoD response with the Office of the Secretary of Defense (OSD), the Joint Staff (JS), and the Navy (the Deputy Chief of Naval Operations (DCNO) for Logistics, N4, coordinates the Navy's response). MARAD only approves a reflagging after confirming "negligible" impact on the military's strategic sealift requirements. In order for USTC to be able to make a sound recommendation, they must know the requisite number of tankers for war.

### 3. Mobility Requirements Study (MRS)

In 1991, Congress requested an "integrated mobility plan" from DoD, resulting in the Mobility Requirements Study (MRS). The study considered the following factors: potential threats, warning time, allied participation, overseas bases and access rights, the availability of commercial shipping, the US civil maritime capability, defense budget pressures, and lessons learned from Operations Desert Shield/Desert Storm (Figure 2). [Macke, 1992, p. ES-1]

The Office of the Secretary of Defense, Program Analysis and Evaluation (OSD (PA&E)) completed a POL tanker study based on the assumptions contained in the MRS study. Before release of OSD's tanker study, MRS BURU (MRS Bottom Up Review - Update) modified underlying assumptions, making the study's results no longer directly applicable [Kross, 1995]. There is currently no official answer as to how many POL tankers DoD requires for war. However, the draft results of a classified study conducted by the Joint Staff's Logistics Directorate, Mobility Division (J4-MOB) were released earlier this year. Their preliminary work provides a valuable starting point, and motivation for, this thesis.

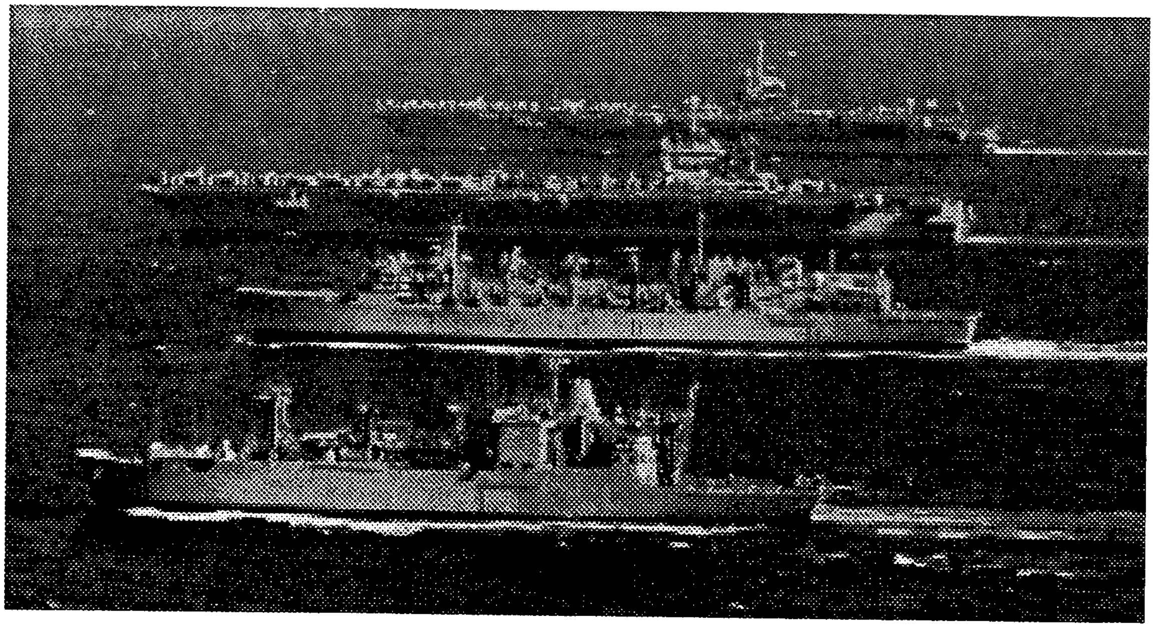

**Figure 2** - As demonstrated during Operations Desert Shield/Desert Storm, the US Navy (USN) is a major user of JP5 fuel. The aircraft embarked on aircraft carriers like ***USS ENTERPRISE*** (top) and ***USS GEORGE WASHINGTON*** (second from top) use this kerosene-based jet fuel. Additionally, it is the fuel source for main propulsion and/or electrical power generation on almost all non-nuclear powered US Navy ships, such as underway replenishment ships ***USS SUPPLY*** (second from bottom) and ***USS MOUNT BAKER*** (bottom). These underway replenishment ships receive JP5 from a shore facility for further transfer to the ships in a battle group [DoD, 1997(b)].

## 4. Current Modeling Process

The Joint Staff is the lead organization currently coordinating efforts to determine the requisite number of POL tankers. The Joint Staff's Logistics Directorate, Mobility Division (J4-MOB), conducted numerous simulations using the Model for Intertheater Deployment by Air and Sea (MIDAS) to determine the minimum number of tankers required for war. MIDAS is a deterministic (no random aspects) model that attempts to answer the following question, "Can the given fuel requirements be met with the given set of sea-lift assets?" Beeker, et al. [1996] describe MIDAS:

> MIDAS is a strategic deployment-scheduling model developed for analysis of airlift, sealift, prepositioning mobility programs of the Department of Defense. MIDAS simulates evolving deployment scenarios ranging from operations-other-than-war (OOTW) to major regional contingencies and to near-simultaneous contingencies. [Beeker, et al., 1996, p. 2-1]

When simulating a large scheduling problem, objectives are developed and weighted with respect to relative importance. The two objectives that receive the heaviest weights in MIDAS are the efficient use of ships and aircraft and the arrival of the units as soon as possible [Beeker, et al., 1996, p. 2-3]. As an example, a problem solved in this thesis, when initially run on MIDAS, delivers all fuel for the entire 75-day window in 30 days, utilizing 60 tankers, each tanker making a single trip. MIDAS feasibly satisfies the fuel requirements. However, any attempt to determine a minimal tanker complement using MIDAS would require numerous runs with numerous changes to the initial starting conditions. Post-run analysis would be manually interpreted, and intelligent changes made to guide MIDAS to select the specific ships, ports to onload fuel, and times to onload fuel, that result in fewer tankers being selected to satisfy fuel requirements.

Enumerating all possible schedules within MIDAS is not practical for many scenarios, so MIDAS uses heuristic decision rules to route ships. Beeker, et al. [1996, p. 2-4] specifically address a limitation of this type of model: "Heuristic methods may be less rigorous than optimization techniques and do not guarantee obtaining an optimal solution." The genesis for this thesis derives from the inability of the Joint Staff to immediately confirm that the feasible schedule provided by MIDAS is optimal. The primary impetus is to create a model that answers "How many POL tankers are required by the DoD to fight and sustain a given war scenario?"

### 5. Problem Statement and Thesis Contribution

To confidently determine the minimal number of tankers required to satisfy war-time fuel requirements, numerous runs are required for each of a set of representative war scenarios. A war scenario, in this thesis, is defined as a set of tankers available for use by DoD, a set of ports for onloading and offloading fuel, and a given set of daily fuel requirements. Each run varies some aspect, or aspects, of the initial conditions that include: fuel requirements (when, where, and type of fuel), tanker availability (when and where they are), the number of available tankers, tanker characteristics (size, speed, draft, fuel capacity, etc.), and port characteristics (draft, production and storage capacities, number of available berths, etc.). Post-run analysis provides a number of tankers, or range on the number of tankers, that would satisfy the fuel requirements across the varied scenarios. If 25 tankers satisfy the requirements across all scenarios, then it reasonable to conclude that 25 tankers would suffice.

MIDAS is accepted by J4-MOB, OSD, and USTC as a valid tool to evaluate war-time planning, and J4-MOB is committed to validating any tanker study results with MIDAS. To determine a minimum number of tankers required, even approximately, for a single scenario could require a very large number of runs in MIDAS. A reduction in the number of runs for a given scenario would expedite the overall time required to determine the minimum number of tankers across various scenarios. This thesis does not demonstrate results across many different scenarios. Rather, it shows results for a realistic scenario provided by J4-MOB, and thereby demonstrates the usefulness of the methodology.

This thesis provides a methodology to help J4-MOB reduce the number of MIDAS runs required to find a minimum number of tankers for any given scenario. The methodology is broken down into two steps. A schedule generator (referred to as "SkedGen") uses known information about tankers, fuel requirements, and ports of embarkation and debarkation, to create output files consisting of feasible schedules for individual tankers. An integer linear program (referred to as "ILP") then determines a subset of these schedules that satisfies fuel requirements with the fewest (approximately) number of tankers. When referring to the collection of Skedgen and ILP, the term MAST (Methodology for Assigning Schedules to Tankers) is used.

### 6. Thesis Outline

Chapter II includes a review of tanker scheduling problems relevant to this thesis. Chapter III includes modeling considerations, assumptions, the mathematical formulation of the schedule generator and the optimization model. Chapter IV describes the application of the model to the J4-MOB Tanker Study problem, the origin of the unclassified data, and results from the computations. Chapter V encompasses recommendations for further research and conclusions drawn from a specific instance of this model. Appendix A contains a list of acronyms, and Appendix B contains the data for the scenario solved in this thesis.

# II. RELATED RESEARCH

The literature of operations research contains a wide variety of articles on tanker scheduling problems. A chronological review of tanker problems starts with Dantzig and Fulkerson [1954]. They minimize the number of tankers required to meet a schedule with fixed pickup and delivery times. McKay and Hartley [1974] minimize operating and purchasing costs of transporting crude oil. Ronen [1983] provides a comprehensive review of cargo scheduling problems in the optimization literature (including tankers), and proposes a classification scheme for categorizing similar problems. Brown, Graves and Ronen [1987] minimize cost for a major oil company's crude oil purchase, tanker-routing and scheduling problems. Fisher and Rosenwein [1989] minimize operating costs using a column-generation technique to create all possible schedules for a Military Sealift Command (MSC) tanker scheduling problem. Pagonis [1995] minimizes arrival lateness of unit cargo at the Sea Port of Debarkation (SPOD). The following paragraphs describe the more relevant aspects of these models, summarize their capability on their test cases (where applicable), and highlight similarities and differences with the model in this thesis.

## A. TANKER SCHEDULING PROBLEMS

Dantzig and Fulkerson [1954] minimize the number of tankers required to meet a "schedule" (a single voyage) with fixed pickup and delivery times. Combinations of "schedules" are added together to make a "sequence." To represent multiple "schedules," the sequence is replicated over time. They assume homogeneity in their tanker fleet, ports and port facilities, that is, they do not account for differing tanker characteristics (e.g., draft, load capacity, availability times, etc.), or differing port characteristics (e.g., berth loading capacities, fuel production or storage capacities, etc.). They demonstrate a tanker-scheduling problem can be converted into a transportation problem. They solve the resulting transportation problem using the simplex algorithm and determine a solution by hand for an 18 day, 7 tanker problem.

Dantzig and Fulkerson's model differs significantly from MAST. MAST accounts for varied tanker and port constraints. Additionally, MAST uses fixed delivery schedules like Dantzig and Fulkerson (with associated penalties for lateness and non-delivery), but not fixed pick-up schedules. The Sea Ports of Embarkation (SPOEs) that provide fuel to the SPODs vary, unlike their model which treats them as fixed.

McKay and Hartley [1974] minimize operating and purchasing costs associated with the transportation of bulk petroleum products by the Defense Fuel Supply Center (DFSC) and the Military Sealift Command (MSC). Their formulation allows for multiple deliveries of multiple products at multiple locations, and partial pick-up and delivery of products (provided it is cost-beneficial). They use an "approximate solution technique" to solve a specific integer linear problem for a "typical" DFSC task. The approximation technique is: Solve the linear programming (LP) relaxation of the problem; look at the size of the fuel loads carried; round up or down any variables that are "close" to one or zero; then re-solve the LP relaxation with these set values. Optimality can not be assured under this technique. The dimensions of the problem they solve include 700-900 integer variables, 2,500 continuous variables, and 1,000 constraints.

McKay and Hartley's model differs somewhat from MAST. MAST allows for multiple deliveries of multiple products at multiple locations, but does not allow for partial deliveries of multiple products (The generated schedules fill the tanker as full as possible, with one type of fuel. A tanker may pick up a different fuel type on another trip, but the model only allows one SPOE, one SPOD, and one type of fuel per trip.). Other differences are that the McKay and Hartley problem is substantially smaller than the one in this thesis, and their objective of minimizing cost is not necessarily equivalent to minimizing tankers.

Ronen [1983] provides a comprehensive review of models and problems associated with scheduling cargo ships. He proposes a classification scheme for cargo scheduling problems and addresses works in the literature (prior to 1983) in these classes. He draws out the differences between cargo-ship scheduling, and other types of transportation scheduling (e.g., bus scheduling, train routing). He groups the cargo-scheduling problems in three different categories of operations: liners, tramps, and industrial. MAST would be classified under Ronen's "industrial" category. His review of works in the industrial category includes the Dantzig-Fulkerson and McKay-Hartley models discussed above. In this category, Ronen also reviews Flood's [1954] model that minimizes empty transit by a cargo ship and thereby minimizes the number of tankers used, Briskin's [1966] model that allows for multiple discharge ports, Bellmore, Bennington and Lubore's [1971] model that allows for a mix of tanker types, and partially loaded tankers [Ronen, 1983, pp. 119-126]. The last three articles each address different aspects of the problem in this thesis and provide background for the more pertinent articles reviewed below.

Brown, Graves and Ronen [1987] solve a major oil company's crude oil tanker routing and scheduling problem. The minimization of the following costs are included: daily cost of owned vessels, the cost of expending fuel during transit (speed dependent), port and canal dues, spot charter costs, and the cost of owning an idle ship. The test problems solved using their model include an 80 day planning horizon, 50 cargoes (up to 25 of which may be spot chartered), a fleet size of 24 ships, and three loading and nine discharging ports. They solve problems with up to 7,349 schedules on an IBM 3033 in under five seconds.

Their model and the one developed in this thesis are very similar. The major difference between their model and MAST is the minimization of cost, and the great fidelity with which it is modeled. Additionally, based on the cost of crude oil being transported, they may change the destination of the ship as the price changes; this is beyond the modeling scope needed in this thesis.

Fisher and Rosenwein [1989] solve a more generic ship scheduling problem by minimizing costs of cargoes carried. Their model, though designed for any bulk cargo, successfully solves an MSC tanker scheduling problem. Their "costs" include the operating cost of the ship in the available fleet, and the cost of a spot charter. They generate a "menu" of all possible schedules, resulting in the formulation of a set-packing problem. They solve the set-packing problem using the dual of a Lagrangian relaxation of the problem. They solve an MSC scheduling problem of delivering 28 cargoes with 17 tankers using less than 800 schedules, using cost data provided by MSC. The solver was written in PASCAL, and run on a VAX 8600 in less than five minutes for the test problem considered.

Differences between the Fisher and Rosenwein model and MAST include: the problem size (30 day planning period, less than 800 schedules, 17 ship tanker fleet); the minimization of costs versus tankers; the consideration of spot charters for transport rather than relying on a given fleet of tankers; and the treatment of cargoes as "fixed quantities" of fuel (given two 300,000 barrel "cargoes" and only one 550,000 barrel capacity ship, the Fisher-Rosenwein model would deliver one cargo of 300,000 barrels. In contrast, MAST would transport the maximum ship capacity, 550,000 barrels.). The greatest similarities are the inclusion of port and tanker characteristics, and that they are modeled in great detail (depth, storage capacity, load/unload times, ship availability windows, etc.) in both the Fisher-Rosenwein model and MAST.

Pagonis' strategic sealift optimization model determines the best set of schedules for cargo vessels, minimizing penalties associated with: port loading, ship berthing, and cargo not transported [Pagonis, 1995]. The structure for his model was the most insightful in developing MAST. He uses data similar to the type used during war planning, and considers single- and dual-front war scenarios, using implicit and explicit delays for delivery of units. The most demanding scenario from a computational standpoint was a dual-front war scenario. The 2,027 schedules take just under twenty minutes to generate, and yield a solution guaranteed to be within 6.33 percent of the optimal solution in 2 hours and 15 minutes on an IBM RS/6000 Model 590. [Pagonis, 1995, pp. 34-43].

The major differences between Pagonis' model and MAST are that unit-type cargo modeled in Pagonis' (tanks, vehicles, etc.) requires a single delivery, is only available at one SPOE, and is to be delivered to only one SPOD. In contrast, POL tankers modeled in MAST may make multiple trips from a single SPOE to the same SPOD, with the same cargo. Or, POL tankers may make multiple trips from various SPOEs to various SPODs, with various cargoes.

## B. SIMULATION MODEL

### 1. Model for Intertheater Deployment by Air and Sea

The Model for Intertheater Deployment by Air and Sea (MIDAS) program is the tool used by J4-MOB to conduct simulations to determine the minimum number of tankers required for war.

The main objectives in MIDAS are the earliest possible delivery of forces, the arrival of forces in the order required (e.g., FT Benning troops must arrive prior to the troops from FT Hood), the on-time arrival of supplies for sustainment, efficient use of ships and aircraft, and maintaining the integrity of the military units [Beeker, et al., 1996, p. 2-3]. MIDAS uses a heuristic, a "greedy search algorithm," to maximize the utilization of each ship [Beeker, et al., 1996, p. 2-4].

A limitation of this type of model is that "Heuristic methods may be less rigorous than optimization techniques and do not guarantee obtaining an optimal solution." [Beeker, et al., 1996, p. 2-4]. This limitation can be problematic: When MIDAS provides a satisfactory solution to a scenario, MIDAS has served its purpose. However, when

MIDAS provides an unsatisfactory answer, it could be caused by the scenario or by the heuristics. The inability to guarantee that the schedule derived is optimal is the primary impetus for the development of MAST.

# III. OPTIMIZATION MODEL

## A. PROBLEM DEFINITION

### 1. Ship Classes

There exist four classes of tankers germane to this study: US-flagged vessels (Figure 3) are commercial tankers owned by US companies, their subsidiaries or US citizens; MSC-controlled tankers are owned and operated by the MSC; Effective US Controlled (EUSC) tankers are those vessels that fly a flag of the Honduras, Bahamas, the Republic of the Marshall Islands, Panama or Liberia and are available during war for use by US forces; and the Ready Reserve Force (RRF) tankers owned by MARAD, which remain in a Reduced Operating Status (ROS). This status indicates the tankers can be fully operational in a pre-designated period of time (either ten or twenty days).

### 2. Objectives

DoD controls, and has available for planning and use, the MSC and RRF tanker fleets. However, DoD must determine the minimum number of additional POL tankers (whether US-flagged or EUSC) required to fight a war (or a given set of war scenarios). If DoD can accurately quantify the required number of tankers, it can confidently respond to MARAD with concrete numbers. In turn, MARAD can respond quickly to commercial industry.

Quantifying the number of tankers required is non-trivial. There is no commonly defined "tanker." For planning purposes, the Joint Staff (JS) has defined five "types" of tankers used in the Mobility Requirements Study (MRS) [Kross, 1996, Enclosure C]. This type-casting divides the tankers based solely on POL capacity. No regard is given to other tanker characteristics (e.g., length, breadth, width, or draft), and within each division all tankers are treated equally. Tanker types should be based on more applicable measures of effectiveness (not necessarily capacity).

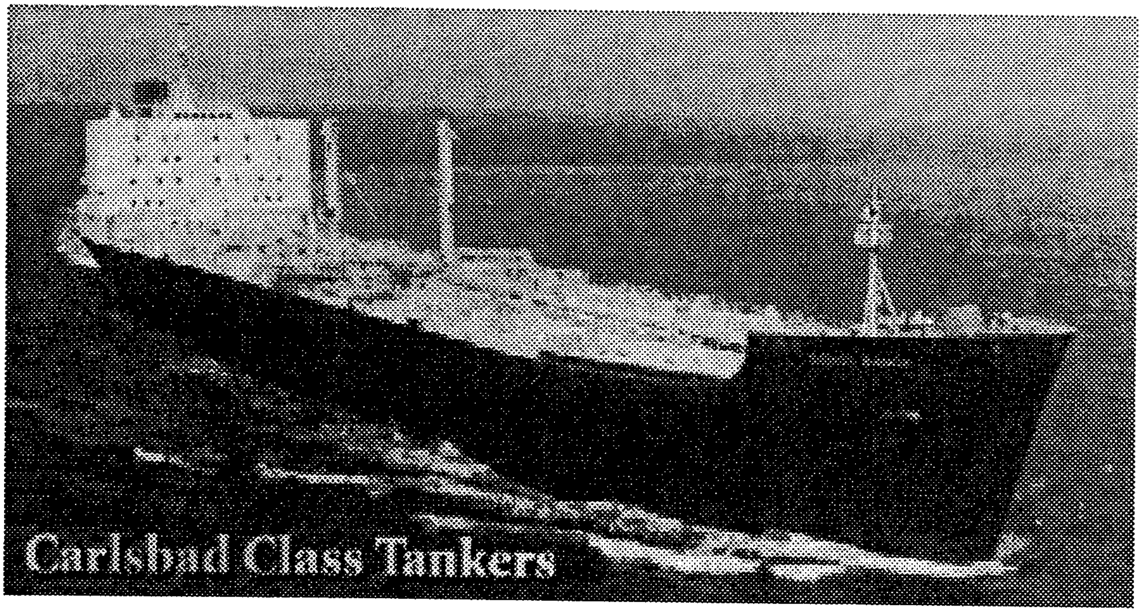


**Figure 3** - ***SS COAST RANGE***, another medium-sized, US-flagged tanker, has a draft of 33 feet, a speed of 17 knots, and a capacity of 320,000 barrels of fuel [NASSCO, 1997(b)].

## B. MODELING CONSIDERATIONS

The primary goal of this thesis is to develop a methodology for determining the minimal number of tankers to satisfy war-time fuel requirements for a given scenario, with a specific set of initial conditions. MAST generates all "feasible" schedules (taking into account characteristics of the tankers and ports that do not exceed limitations such as draft, storage capacity, production capacity, etc.) for individual tankers (utilizing SkedGen, written in PASCAL), creates an integer linear program (ILP) from these schedules, and solves the ILP to determine the "best" combination of schedules. The "best" combination is the set of schedules that uses the fewest tankers, and delivers all fuel as close as possible to requirement timelines.

Modeling considerations include both general considerations and those specific to SkedGen and the ILP. The considerations outlined below define the structure of a war-time scenario. These considerations outline the required information necessary for MAST to select a minimal number of tankers for the scenario as well as the type of problem being solved.

### 1. General Considerations

The current usage of POL by DoD during peacetime operations is 98 percent bulk fuel and 2 percent "other" [Quiroga and Strength, 1996, p. 1]. It is expected that these usage percentages will continue to hold, and that the modeling of these major fuel types (JP5 and JP8) is sufficient (Figure 4).

A single speed is assumed for each tanker, its "most efficient" speed. This speed is used in the inter-port time computations as follows: A tanker that transits from Pearl Harbor, Hawaii to Diego Garcia travels 9,775 nautical miles (nms). Divide this distance by the ship's assumed 16-knot speed and the result is 610.9375 hours, or 25.46 days. For purposes of this thesis, this is rounded up to 26 days.

A "pumping day" is 200 mbbls (thousand barrels) per day. To determine onload/offload times, the amount of fuel to be transferred is divided by 200 mbbls, and the time is rounded up to the nearest whole day. The model accounts for the fuel production limits and storage capacities at the SPOEs and SPODs. The fuel requirements are the net requirements, for any given day, at the SPODs. There is a desirable "buffer" or fuel reserve of 15 days, specific to an SPOD, it is pre-designated, and is included in these net fuel requirements.

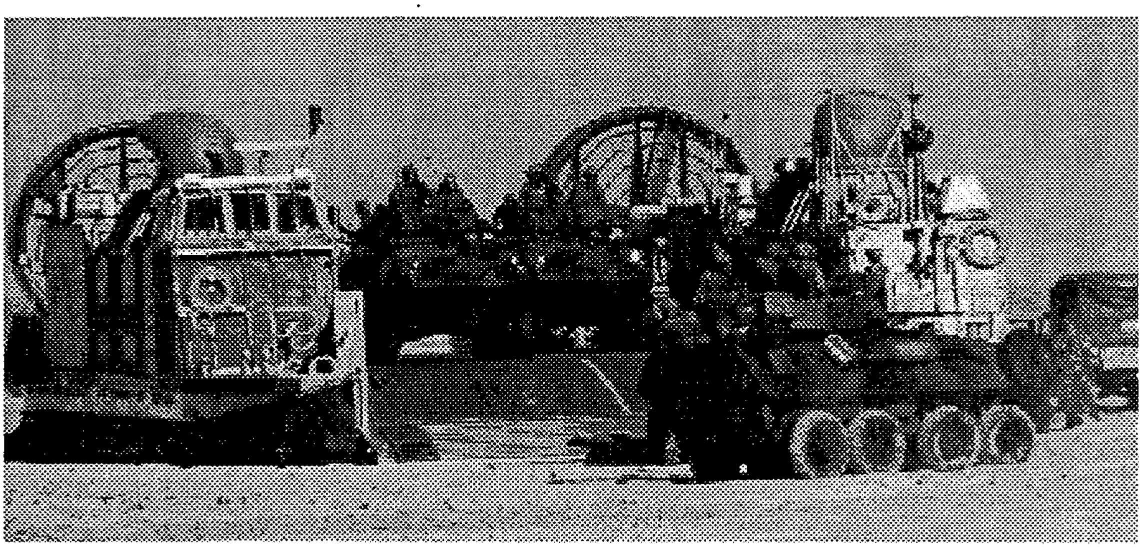

**Figure 4 -** The Landing Craft-Air Cushion (LCAC) offloads armored and conventional personnel carriers which both utilize JP5 fuel. The LCAC, a hovercraft, can carry a 60 ton M1A1 Abrams tank up to 60 nautical miles, at speeds of up to 60 knots, on a cushion of air. This capability of transporting troops past the beach and inland to more secure areas requires a large expenditure of fuel [DoD, 1997(c)].

## 2. Schedule Generator Considerations

To generate schedules for the individual tankers, SkedGen allows, time permitting, for each ship to make up to five "deliveries" of fuel. The time window for creating schedules is set at 75 days (this can be changed). A unique combination of SPOE, pickup date, amount of fuel, fuel type, SPOD, and drop off date make up each delivery. SkedGen's smallest unit for measuring time is a day.

The following events associated with SPOEs (SPODs) that take time are aggregated: pulling in and out of port; setting up (breaking down) pumping stations; and time to onload (offload) fuel. This sum is then rounded up to the nearest day, and added to the inter-port transit time to determine when the tanker is ready to onload (offload) fuel at the next SPOE (SPOD).

The first day a tanker is available for onloading fuel, and the closest port to that tanker for onloading fuel are both determined prior to running SkedGen and provided as data (the initial SPOE, and the day the tanker arrives at the SPOE). The calculations include the time to complete the current delivery of fuel, the transit from initial position at time 0 to original destination, the offload time, the transit to initial SPOE (applicable to US-flagged, MSC and EUSC ships with fuel onboard) and any time required to activate ships (RRF only). A tanker's initial availability (both the place and time) are initial conditions that specifically define a given run.

SkedGen creates schedules that include the following information: when a ship onloads a specified amount of a certain fuel, at an SPOE, for delivery to an SPOD, on a specific day. Figure 5 shows an example of a specific schedule for the ***SS COAST RANGE***.

**SS COAST RANGE,** Schedule 4503

Time (in days)

| | | | |
|---|---|---|---|
| 0 | Enroute to Pearl Harbor | 27 | Enroute Pearl Harbor |
| 3 | Arrive at Pearl Harbor | 49 | Arrive at Pearl Harbor |
| 3 | Onload 220 mbbls, of JP5 | 49 | Onload 320 mbbls of JP8 |
| 4 | Complete Onload | 50 | Complete Onload |
| 4 | Enroute to Diego Garcia | 50 | Enroute Jeddah |
| 26 | Arrive at Diego Garcia | 72 | Arrive at Jeddah |
| 26 | Offload 220 mbbls of JP5 | 72 | Offload 320 mbbls of JP8 |
| 27 | Complete Offload | 73 | Complete Offload |

**Figure 5** - The schedule generator (SkedGen) computes the transit time between ports based on distance tables and tanker speeds. SkedGen does not: send a tanker to a draft prohibiting port, overfill tankers, onload more fuel than available, offload more fuel than carried onboard, nor offload more fuel than the SPOD can store. A specific ship, ***SS COAST RANGE,*** transits to Pearl Harbor to onload 220 mbbls of JP5 for delivery to Diego Garcia and returns to Pearl Harbor to onload 320 mbbls of JP8 for Jeddah, Saudi Arabia. Note that the offload at Diego Garcia on the first trip is only 220 mbbls which is Diego Garcia's storage capacity. Note that the schedule is complete after day 73 because the ship can not complete another SPOE-SPOD transit within the 75 day limit.

## 3. Integer Linear Programming Considerations

This section describes the ILP that selects the combination of schedules that satisfy the fuel requirements with the fewest number of tankers. When ships share similar characteristics, they may be aggregated into a "tanker group." Since it may be impossible to satisfy some fuel requirements (a specific amount of a specific type of fuel, on a specific day) with existing assets, the model uses elastic constraints for non-delivery of fuel and the use of fuel reserves. Elastic constraints allow violation, but any violation incurs a linear penalty per unit violation.

## C. MODEL FORMULATION

### 1. Indices

| | |
|---|---|
| **d** | POD, (d = Cairo, Diego Garcia, . . . , Thailand); |
| **e** | POE, (e = Al Jubail, Amuay Bay, . . . , UK); |
| **f** | fuel type (f=JP5, JP8 ); |
| **i** | ship, (i = ALATNA, ALMA, . . . , VEGA); |
| **s** | schedules, (s = 1, 2, . . . , S); and |
| **t** | time (in days), (t = 1, 2, . . . , T). |

### 2. Data

| | |
|---|---|
| $\mathbf{Pen}_{i,s}$ | Total penalty associated with tanker i, using schedule s; |
| $\mathbf{DevPen}_{d,f,t}$ | Penalty for fuel requirements satisfied from the buffer at SPOD d, fuel type f, on day t; |
| $\mathbf{UnDelPen}_{d,f,t}$ | Penalty for unsatisfied fuel requirements at SPOD d, fuel type f, on day t; |
| $\mathbf{ShipSked}_{i}$ | Number of schedules for tanker i. It is 1 if i corresponds to a single tanker, and if i corresponds to a group, then it is equal to the number of tankers in the group; |
| $\mathbf{Rqmt}_{d,f,t}$ | Daily fuel requirement at SPOD d, of fuel type f, at time t, in mbbls; |
| $\mathbf{FuelProd}_{e,f}$ | Daily fuel production capacity, at SPOE e, of fuel type f, in mbbls; |
| $\mathbf{StoragePOE}_{e,f}$ | Fuel storage capacity at SPOE e, of fuel type f, in mbbls; |
| $\mathbf{StoragePOD}_{d,f}$ | Fuel storage capacity at SPOD d, of fuel type f, in mbbls; |

| | |
|---|---|
| **Buffer** $_{d,f}$ | Fifteen day fuel reserve required at SPOD d, of fuel type f, in mbbls; |
| **InitPODInv** $_{d,f}$ | Initial inventory at SPOD d, of fuel type f, in mbbls; |
| **POELimit** $_{e}$ | The maximum number of ships allowed to visit SPOE e, during a specified number (POEWindow) of consecutive days; |
| **POEWindow** $_{e}$ | A specified number of days, that when coupled with the POELimit, preclude port overcrowding; |
| **PODLimit** $_{d}$ | The maximum number of ships allowed to visit SPOD d, during a specified number (PODWindow) of consecutive days; |
| **PODWindow** $_{d}$ | A specified number of days, that when coupled with the PODLimit, preclude port overcrowding; |
| **Here** $_{e,f,t}$ | The set of tanker-schedule combinations that offload at POE e, fuel type f, between times t-POEWindow$_e$ and t; |
| **Here** $_{d,f,t}$ | The set of tanker-schedule combinations that onload at POD d, fuel type f, between times t-PODWindow$_d$ and t; |
| **MBblsIn** $_{i,s,e,f,t}$ | Amount of fuel received by ship i, in schedule s, at POE e, of fuel type f, at time t, in mbbls; |
| **MBblsOut** $_{i,s,d,f,t}$ | Amount of fuel delivered by ship i, in schedule s, at POD d, of fuel type f, at time t, in mbbls; |
| **MaxPOEFuel** $_{e,f}$ | The maximum amount of fuel onloaded to tankers at SPOE e, of fuel type f, in mbbls. MaxPOEFuel can not be exceeded during a specified number (MEF) of days; |
| **MEF** $_{e,f}$ | The number of consecutive days where MaxPOEFuel can be onloaded at SPOE e, of fuel type f; |

**MaxPODFuel $_{d,f}$** The maximum amount of fuel delivered by tankers at SPOD d, of fuel type f, in mbbls. MaxPODFuel can not be exceeded during a specified number (MDF) of days; and

**MDF $_{d,f}$** The number of consecutive days where MaxPODFuel can be offloaded at SPOD d, of fuel type f.

**3. Binary Variables**

**X $_{i,s}$** 1 if ship i uses schedule s, 0 otherwise.

**4. Continuous Variables**

**FuelPOE $_{e,f,t}$** Fuel produced at SPOE e, of fuel type f, at time t, in mbbls;

**MBblsDev $_{d,f,t}$** Fuel requirements satisfied from the buffer at SPOD d, fuel type f, on day t, in mbbls;

**UnDlvrd $_{d,f,t}$** Unsatisfied fuel requirements at SPOD d, fuel type f, on day t, in mbbls;

**FuelAvailPOE $_{e,f,t}$** Fuel available at SPOE e, of fuel type f, at end of day t, in mbbls; and

**FuelAvailPOD $_{d,f,t}$** Fuel available at SPOD d, of fuel type f, at end of day t, in mbbls.

## 5. Equations

**Minimize:**

$$\sum_{i,s} Pen_{i,s} * X_{i,s} + \sum_{d,f,t} UnDelPen_{d,f,t} * UnDlvrd_{d,f,t} + \sum_{d,f,t} DevPen_{d,f,t} * MBblsDev_{d,f,t} \tag{1}$$

**Subject To:**

$$\sum_{s} X_{i,s} \leq ShipSked_i \qquad \forall\, i \tag{2}$$

$$\sum_{\substack{i,s \\ t' \leq t}} MBblsOut_{i,s,d,f,t'} * X_{i,s} + InitPODInv_{d,f} \geq \sum_{t' \leq t} Rqmt_{d,f,t'} - MBblsDev_{d,f,t} - UnDlvrd_{d,f,t} \qquad \forall\, d, f, t \tag{3}$$

$$MBblsDev_{d,f,t} \leq Buffer_{d,f} \qquad \forall\, d, f, t \tag{4}$$

$$FuelAvailPOE_{e,f,t} = FuelAvailPOE_{e,f,t-1} + FuelPOE_{e,f,t} - \sum_{i,s} MBblsIn_{i,s,e,f,t} * X_{i,s} \qquad \forall\, e, f, t > 0 \tag{5}$$

$$FuelPOE_{e,f,t} \leq FuelProd_{e,f} \qquad \forall\, e, f, t \tag{6}$$

$$FuelAvailPOE_{e,f,t} \leq StoragePOE_{e,f} \qquad \forall\, e, f, t \tag{7}$$

$$\sum_{\substack{i,s \\ t' \leq t}} MBblsOut_{i,s,d,f,t'} * X_{i,s} + InitPODInv_{d,f} - \sum_{\substack{i,s \\ t' \leq t}} Rqmt_{d,f,t'} \leq StoragePOD_{d,f} \qquad \forall\, d, f, t \tag{8}$$

| | | |
|---|---|---|
| $X_{i,s} \in \{0,1\}$ | $\forall$ i,s | (9) |
| $FuelPOE_{e,f,t} \geq 0$ | $\forall$ e, f, t | (10) |
| $MBblsDev_{d,f,t} \geq 0$ | $\forall$ d, f, t | (11) |
| $UnDlvrd_{d,f,t} \geq 0$ | $\forall$ d, f, t | (12) |
| $FuelAvailPOE_{e,f,t} \geq 0$ | $\forall$ e, f, t | (13) |

## 6. Description of Equations

The objective function (1) minimizes the sum of all penalties, which are described in section 8 below.

Constraint (2) ensures that each tanker is assigned at most one schedule; **ShipSked**$_i$ has value 1 when i corresponds to a single tanker or it is the number of tankers in the "tanker group". Constraint (3) ensures fuel requirements are met on time, but contains elastic variables for delivery shortages. There are two types of delivery shortages, designated **MBblsDev** and **UnDlvrd.** **MBblsDev** is the amount of fuel reserves required to satisfy fuel type f requirements at SPOD d, on day t. **UnDlvrd** is unsatisfied fuel type f requirements at SPOD d, on day t. Constraint (4) ensures fuel reserve use does not exceed the fuel buffer. Constraint (5) is the daily inventory flow-balance constraints associated with the SPOEs. Constraint (6) precludes the production of more oil than is feasible. Constraint (7) precludes the model, on a daily basis, from onloading more fuel from an SPOE than can be stored there. Constraint (8) precludes the model from delivering more fuel to an SPOD than can be stored. Sufficient SPOD storage was found for the given scenario, thus constraint (8) was removed from the ILP to reduce the size of the model.

## 7. Alternative Equations

Alternative equations can be used when formulating this problem. Although not used in the solution of the scenario in Chapter IV, they may prove more effective on a different scenario.

$$\text{FuelAvailPOD}_{d,f,t} = \text{FuelAvailPOD}_{d,f,t-1} + \sum_{i,s} MBblsOut_{i,s,d,f,t} * X_{i,s} + \text{Rqmt}_{d,f,t} +$$

$$\text{MBblsDev}_{d,f,t} + \text{UnDlvrd}_{d,f,t} \qquad \forall\ d, f, t > 0 \qquad (15)$$

$$\sum_{\substack{i,s \\ t-MEF_{e,f} \le t' \le t}} MBblsIn_{i,s,e,f,t'} * X_{i,s} \le MaxPOEFuel_{e,f} \qquad \forall\ e, f, t \ge \text{MEF}_{e,f} \qquad (16)$$

$$\sum_{\substack{i,s \\ t-MDF_{d,f} \le t' \le t}} MBblsOut_{i,s,d,f,t'} * X_{i,s} \le MaxPODFuel_{d,f} \qquad \forall\ d, f, t \ge \text{MDF}_{d,f} \qquad (17)$$

$$\sum_{i,s \in Here_{e,f,t}} X_{i,s} \le POELimit_e \qquad \forall\ e, f, t \qquad (18)$$

$$\sum_{i,s \in Here_{d,f,t}} X_{i,s} \le PODLimit_d \qquad \forall\ d, f, t \qquad (19)$$

Equation (15), similar to equation (3), is the daily flow balance constraint for the SPOD. Equation (16) is similar to the flow balance constraint for the SPOEs, equation (5). It precludes the model from onloading more fuel than a port can supply over a user-defined period of days. Equation (17) provides this function for the SPODs, precluding the offloading of too much fuel to the port, over a given period of days. Equations (18) and (19) prevent port overloading.

### 8. Penalties

The penalty scheme described below encourages a pre-specified hierarchy in the ILP. Penalties are associated with each tanker dependent upon ship class and capacity, and the violation of elastic constraints. The ship classes (MSC, RRF, EUSC, and US-flagged) and capacities (mbbls of fuel that can be transported) uniquely define each tanker's penalty. Penalties for unsatisfied fuel requirements, and those fuel requirements satisfied by depleting the reserves are picked in relation to tanker penalties.

It is always preferable to use RRF and MSC tankers prior to using EUSC or US-flagged tankers. RRF and MSC tankers are owned and operated by the government (DoD

for the MSC tankers, DoT for the RRF tankers), and available for war. As a result of this preference, no penalties are assigned for the use of RRF and MSC tankers.

The ship class with the next highest usage preference is the EUSC class. The penalty for a ship in the EUSC fleet is set equal to the tanker's capacity.

To encourage the use of US-flagged tankers last, the penalty for a tanker in this class is set to the individual tanker's capacity plus that of the maximum capacity of the EUSC flag fleet tankers (676).

The penalties per mbbl of fuel in the MBblsDev category (fuel requirement satisfied by the fuel reserves) and in the UnDlvrd category (unsatisfied fuel requirements) are 1 and 2 respectively. If the fuel shortage for a given day can be satisfied by using some of the fuel reserves, then the forces can still operate (the reserve is depleted to some degree). But, if the amount of fuel shortage exceeds the fuel reserve capacity, the operational commander does not have sufficient fuel available to conduct operations (the reserve is empty). Thus there is distinction, and larger penalty, on the amount of undelivered fuel in excess of the reserve level. MBblsDev and UnDlvrd are each measured in mbbl-day, or thousands of barrels per day of requirements that are not met.

This penalty structure ensures that a small amount of undelivered fuel at a SPOD, or SPODs, does not force the utilization of a previously idle tanker. However, a total shortfall of undelivered fuel-days that, for instance, exceeds the capacity of an EUSC tanker that can satisfy the shortfall, forces the ILP to select the tanker. For example, if there is an undelivered amount of fuel at a port for two consecutive days of 60 mbbls, and the port's Buffer is 25 mbbls, the computed penalty using constraint (3) is 190 mbbl-days. A penalty of 50 mbbl-days, associated with MBblsDev, is the product of 25 (for the deviation, in mbbls), two (number of days), and one (amount of penalty per mbbl). And a penalty of 140 mbbl-days, associated with UnDlvrd, is the product of 35 (for the undelivered amount, in mbbls), two (number of days), and two (amount of penalty per mbbl). The sum of these two penalties is 190 mbbl-days. Therefore the ILP would select any tanker schedule that delivers at least 60 mbbls prior to the first day of shortage and has a penalty less than 190 mbbls (all RRF and MSC tankers have zero penalty, and any EUSC tanker with penalty less than 190 would be appropriate).

# IV. COMPUTATIONAL RESULTS

## A. SCENARIO DESCRIPTION

The scenario solved in this thesis is provided by J4-MOB. It spans a 75-day planning period, and is defined by the set of SPOEs that produce fuel, the set of SPODs that require fuel, the tanker assets available, and the fuel requirements (per fuel type and day) at the SPODs. The set of seven SPODs that require fuel, with characteristics, are listed in Appendix B, Table 3. The set of 16 SPOEs that provide fuel, with their characteristics, are listed in Appendix B, Table 4. The available tanker fleet consists of 92 tankers, each categorized in one of four ship classes, RRF, MSC, EUSC, or US-flagged (Appendix B, Table 5 contains a subset of these tankers, and their characteristics). A subset of the 13,518 mbbls total fuel requirement, listed by SPOD, fuel type and day is contained in Appendix B, Table 6. The distances used in the thesis are contained in Appendix B, Table 7 with the SPOEs down the first column and the SPODs across the top.

## B. RESULTS

J4-MOB provided the unclassified data used in this thesis in Microsoft Excel Spreadsheets. After rearranging the data format, it was saved as space delimited files (*.prn extension) and comma delimited files (*.csv). The space delimited format served as the input for the model generator which is written using the General Algebraic Modeling System (GAMS) [Brooke, et al., 1992]. The comma delimited files serve as input for SkedGen. SkedGen was written in PASCAL, and writes output files in ASCII text format (*.txt). SkedGen runs on a Dell OptiPlex GXPro Personal Computer with a Pentium Pro 200 megaHertz processor. The ILP is solved on an IBM RS/6000 Model 590 workstation using GAMS to generate the model and either OSL [Wilson, et al., 1992] or CPLEX [CPLEX Optimization, Inc., 1994] to solve it.

### 1. Methodology for Assigning Schedules to Tankers (MAST)

An upper bound on the number of possible schedules for this scenario is over 3.2 trillion. A tanker's first trip has a pre-selected SPOE, coupled with two fuel types and seven SPODs; there are a maximum of 14 combinations possible. For trips 2-5, there are 16 SPOEs, two fuel types, and seven SPODs, and therefore 224 possible combinations. The upper bound is the product of the number of tankers and the number of possible schedules for each trip, 92 * {14 * 224 * 224 * 224 * 224}, approximately 3.2 trillion. Trying to manually determine the best combination from over 3.2 trillion schedules would be exceedingly difficult.

SkedGen creates only schedules that deliver the required fuel type, to the desired SPODs, utilizing tankers that are not prohibited by the draft at the SPOD. For the 92 tankers, 7 SPODs, 16 SPOEs and a 90-day window for planning (reduced to a 75-day window in section 3 below), SkedGen created over 798,000 feasible schedules in 1 hour 45 minutes. This is unnecessarily large, and further reduction is required to solve the problem. The following paragraphs outline a systematic process to reduce the number of schedules, and produce a manageable number of "smart" schedules for the ILP.

### 2. Modeling Groups of Tankers

Different tankers can be intelligently aggregated. Tankers in the same class (EUSC, MSC, etc.) with fuel capacities within 5 mbbls and speeds within 2 knots of each other were collected into groups. For example, the Projected Tankers (twelve total) differed only in their initial SPOEs and initial delays. Thus they were grouped. This aggregation of similar tankers reduced the number of tankers from 92 to 26 tanker "groups." Appendix B, Table 8 contains the merged tanker groups, and the number of each available. Other inputs remained the same.

Some fidelity is lost in this grouping since the group of tankers has the same initial SPOE and initial delay, but the reduction in schedules generated is substantial. With tanker groups, SkedGen created 289,661 feasible schedules in 39 minutes. The

cumulative size of the 30 output files was 172 megabytes. The largest number of schedules for a tanker "group" was 56,263. An attempt to solve the corresponding ILP took over 30,000 central processor unit (cpu) seconds (8 hours and 20 minutes of cpu time) and returned an integer solution guaranteed to be within 17 percent of the optimal. Generating this problem required 1.9 gigabytes of RAM, and the full generation/solution process required roughly 16 hours. The results were promising, but the determination of a subset of schedules that would enable the ILP to solve the problem more quickly required more work.

### 3. Planning Horizon Reduction

The next attempt to reduce the number of schedules generated involved reducing the planning horizon from 90 to 75 days. The war may last longer than 75 days, but the early part of the conflict, when meeting the surge phase requirements, requires the greatest number of tankers. The fuel requirements in the sustainment phase begin to approach a "steady-state" condition. Thus, it is reasoned that the minimum number of tankers required for surge will suffice during the sustainment phase, and 75 days is sufficient to model the surge phase.

SkedGen, limited to a 75-day scheduling window, created 26,900 feasible schedules in 4 minutes, 20 seconds. The cumulative size of the 30 output files was 14 megabytes. The largest number of schedules for any tanker group was 5,910. The linear programming (LP) relaxation of this set of schedules was solved in 469 cpu seconds, requiring only 249 megabytes of RAM, but an integer solution was not obtained in 100,000 cpu seconds (a limit of 100,000 cpu seconds was set).

This "baseline" iteration (Run 1, Table 1) includes the schedule reduction due to tanker grouping and reducing the window to 75 days. The LP relaxation of the 26,900 feasible schedules results in an objective function value of 9,476. It uses 15.38 tankers (2.01 RRF, 7.33 MSC, 4.47 EUSC, and 1.57 US-flag). All fuel requirements are met, but not on time, with 438 mbbl-days of fuel being delivered late. (Mbbl-days is not the

cleanest measure of effectiveness, but it is indicative of the ability to deliver fuel on time.) The LP relaxation is referred to as the "base case," and provides a lower bound on the best possible integer solution.

### 4. MAST's Results

The 19 tankers (eight US-flagged) selected in Table 1, Run 4 is the best solution found by MAST. It is found by grouping the tankers, reducing the planning horizon, and limiting the number of schedules considered to 17,231. The 17,231 schedules were found using the iterative process outlined in section 6. The best integer solution has an objective function value of 17,914 (189 percent of the base case objective function value, guaranteed to be within 49.9 percent of the best integer solution for this set of schedules). The amount of fuel not delivered on time is 608 mbbl-days, which is only slightly higher than the base case. This satisfies 95.5 percent of all fuel requirements on time, and delivers 98.99 percent of all fuel required. The tankers selected, and their characteristics, are outlined in Table 2.

The shortfall of undelivered fuel is a result of the timing, rather than the lack of available tankers. Specifically, a tanker delivering 137 mbbls of fuel on day 30 to Guam would satisfy all fuel requirements on time. However, the crux of the problem is that the shortage occurs during the surge phase, and there are no uncommitted tankers available to deliver by day 30. The earliest any tanker can deliver JP8 to Guam with the schedules considered, is by day 32, only one tanker can do it, and that schedule was already selected. In fact, the next available schedule that delivers JP8 to Guam is not until day 35, and that schedule was also selected.

This highlights a drawback of the tanker grouping methodology outlined above. The grouping of the tankers eliminates some feasible schedules with different initial SPOEs and initial delays that could result in a delivery of JP8 to Guam, prior to the day the shortfall arises. In fact, the tanker that delivers on day 35 is in the group of six MSC tankers (which incur no usage penalty), and only one was selected. A manual or computer-aided review of the 52,860 schedules not available to the ILP (eliminated during

the grouping process), could reveal tankers in this group that deliver JP8 to Guam by day 30. If such a schedule is found, it could be re-introduced into the ILP.

***Final Results***

| Run | Schedule Generation (seconds) | Number Schedules | Optimization (cpu secs) | Number of Avail Tanker Groups | Planning Horizon (days) | Number of Tankers | Number of US Flag Tankers | Undelivered Fuel (mbbl-days) |
|---|---|---|---|---|---|---|---|---|
| 1 | 260 | 26,900 | >100,000 | 26 | 75 | N/A | N/A | N/A |
| 2 | 260 | 2,875 | 739 | 26 | 75 | 16 | 7 | 1,916 |
| 3 | 260 | 8,467 | 6,050 | 26 | 75 | 17 | 8 | 829 |
| 4 | 260 | 17,231 | 18,949 | 26 | 75 | 19 | 8 | 608 |
| 5 | 260 | 17,231 | 25,186 | 26 | 75 | 15 | 5 | 284 |

**Table 1 -- Final Results.** The time for the schedule generator run on a personal computer represents real-world time, rather than cpu seconds. The optimization time was computed on the IBM RS/6000 Model 590, utilizing GAMS, and the CPLEX solver. The undelivered fuel is cumulatively measured in mbbl-days. If the amount undelivered on day 35 is 90 mbbls, and it takes five days before the requirement is met, the amount reported in the last column is 450 mbbl-days. In the fourth run, a delivery of 137 mbbls to Guam of JP8 before day 32 would result in no undelivered fuel. The total mbbls required during the 75 days is 13,518 mbbls. The final run (run four) delivers 98.99 percent of the required fuel [{(13,518 - 137)/13,518}* 100% ]. Run five is an excursion with a ten percent reduction in fuel requirements.

### 5. MIDAS' Results

The scenario solved in this thesis was run on MIDAS. Initially, MIDAS delivered the 75-day fuel requirement in 30 days with 60 tankers. MIDAS delivered the fuel quickly, without regard to the number of tankers, due to the heavy weighting associated with the objective function in MIDAS, minimize lateness. Consequently, delivering fuel early, regardless of the number of tankers required, produced a better MIDAS objective function value. When running this scenario with the MAST output, MIDAS satisfied the fuel requirements with 19 tankers, in 74 days. This demonstrates the usefulness of using MAST with MIDAS to reduce the number of runs for a given scenario.

***Selected Tankers***

| Short Ship Name | Draft | Speed | Capacity | ISPOE | IDelay | ATime | LProd | SType | SClass | Number |
|---|---|---|---|---|---|---|---|---|---|---|
| JURONG | 20 | 12 | 36 | PHILLY | 14 | 0 | CPP | Sh Dr | EUSC | 1 |
| PAGODA | 34 | 14 | 275 | AMUAYBAY | 13 | 0 | CPP | Med | EUSC | 1 |
| LUCY | 44 | 15 | 457 | SPAIN | 11 | 0 | CPP | Large | EUSC | 1 |
| ELBE | 62 | 15 | 455 | SPAIN | 9 | 0 | CPP | Large | EUSC | 1 |
| HANK | 23 | 14 | 48 | PULAUBUKOM | 5 | 0 | CPP | Sh Dr | MSC | 2 |
| KEN | 31 | 13 | 142 | OKINAWA | 7 | 0 | CPP | Sm | MSC | 1 |
| COBB | 36 | 16 | 239 | LONGBEACH | 17 | 0 | CPP | Med | MSC | 1 |
| MCAP | 36 | 17 | 303 | NEWORLEANS | 24 | 20 | None | Med | RRF | 2 |
| NODAWAY | 16 | 10 | 31 | OKINAWA | 11 | 10 | None | Sh Dr | TT | 1 |
| RANGER | 33 | 16 | 308 | AMUAYBAY | 17 | 0 | CPP | Med | USFLAG | 1 |
| PHILASUN | 33 | 16 | 233 | LONGBEACH | 22 | 0 | CPP | HST | USFLAG | 1 |
| MORSKY | 35 | 16 | 283 | LONGBEACH | 26 | 0 | CPP | Med | USFLAG | 1 |
| FALCON | 36 | 16 | 226 | PHILLY | 23 | 0 | CPP | HST | USFLAG | 1 |
| MONSPRAY | 37 | 16 | 275 | NEWORLEANS | 22 | 0 | CPP | Med | USFLAG | 3 |
| JHAMMER | 39 | 16 | 300 | NEWORLEANS | 21 | 0 | CPP | Med | USFLAG | 1 |

**Table 2 --** The tankers selected by the ILP, and their characteristics, can be used to determine shortcomings in fuel requirements, or force structure. The nineteen schedules, taken from the fifteen tanker groups, had three multiple selections (HANK, MCAP, and MONSPRAY).

### 6. MAST's Iterative Process

The "base case" 26,900 schedules failed to yield an integer solution in 100,000 cpu seconds (the resource usage limit specified). Consequently, the number of schedules required reduction. The set of tankers eligible for selection by the ILP were pared down by eliminating tankers that were not selected as part of the solution to the LP relaxation. This reduced the number of schedules from 26,900 to 2,875, eliminating 90.4 percent of the feasible schedules (Run 2, Table 1). An integer solution was achieved (16 total tankers, 7 US-flagged) with an objective function value of 21,622, yet it failed to deliver 1,916 mbbl-days on time (14.2 percent), and 517 mbbls of unmet requirements. This amount of undelivered fuel was seen as excessive, and thus the selection process for the removal of schedules required refinement.

To ensure delivery of more fuel, previously removed schedules were re-introduced (Run 3, Table 1). The tanker schedules that delivered fuel to the ports with shortages were re-introduced. The number of feasible schedules increased from 2,875 to 8,467. An

integer solution was returned with a better objective function value, 18,637, and the total number of tankers selected increased to 17 (an additional US-flagged tanker). The amount of fuel not delivered on time was 829 mbbl-days, (6.1 percent), and the ILP failed to deliver only 434 mbbls.

The final run resulted from re-introducing more schedules, those schedules that delivered fuel to the ports with shortages, on the days the shortages occurred. This resulted in the number of feasible schedules increasing to 17,231, as described in paragraph 5 above.

### 7. Fuel Requirements Reduced

To demonstrate the ability of MAST to accommodate similar scenarios, the scenario provided by J4-MOB was modified (Run 5, Table 1). The reduction of fuel requirements by ten percent results in a reduction of the required tankers from 19 (eight US-flagged) to 15 (five US-flagged). The total fuel requirements dropped from 13,518 mbbls to 12,172 mbbls. The amount of undelivered fuel dropped to 77 mbbls, and 99.39 percent of the fuel requirements were satisfied during the 75 day window. The relationship between the fuel requirements and the number of required tankers is not precisely linear. If so, the expected number of tankers would be 17, versus the 15 that were selected. However, MAST's results are intuitive, the reduction in fuel requirements resulted in a reduction in the number of required tankers.

# V. CONCLUSIONS

## A. CONCLUSIONS

The methodology developed in this thesis, called "MAST", can assists J4-MOB in the effort to determine the minimal complement of POL tankers required to meet fuel transportation requirements for a given war-time scenario. MIDAS is accepted by J4-MOB, OSD, and USTC as a valid tool to evaluate war-time transportation planning, and J4-MOB is committed to validating any tanker study results with MIDAS. To determine a minimum number of tankers required, even approximately, for a single scenario could require a very large number of runs in MIDAS. A reduction in the number of runs for a given scenario would expedite the overall time required to determine the minimum number of tankers across various scenarios. The resulting set of POL tanker schedules provided by MAST can be used to assist MIDAS in minimizing the number of runs required to determine a minimum number of tankers for a given scenario. Without the output from MAST, MIDAS initially delivered 75-days of fuel in 30 days with 60 tankers for the scenario provided by J4-MOB. When running with the schedules provided by MAST, MIDAS satisfied the fuel requirements with 19 tankers, in 74 days. This demonstrates the usefulness of using MAST with MIDAS to reduce the number of runs for a given scenario, and thereby reduce the number of runs across all scenarios.

## B. FUTURE RESEARCH

A complete tanker scheduling system requires additional work. The methodology presented demonstrates the potential value of utilizing an optimization model versus a simulation model for minimizing the number of POL tankers required in a war-time scenario. Limitations of the optimization model could be eliminated with further efforts centered on the areas discussed next.

A more efficient formulation of this problem, exploiting special structure might significantly reduce the solution time. Significant time and effort were expended in the areas of Explicit Constraint Branching [Appelget 1997, pp. 4-8] and priority branching [GAMS, 1992, pp. 281-283], but failed to improve solution time, or the objective function value. Comparisons between different values of terminating conditions (relative distance

from optimality) could be compared to determine the point of diminishing returns with respect to time and the reduction in the number of tankers.

The conversion of the schedule generator into a more robust object-oriented program, coupled with a Graphical User Interface (GUI) would be beneficial to a user with little or no knowledge of mathematical programming. The GUI should link the schedule generator and the ILP to allow the user to "launch" the two programs with a single command. The GUI could initiate the schedule generator, the ILP, and output the results in an environment that would allow the user to easily conduct post-run analysis.

J4-MOB currently conducts POL tanker runs and container ship runs independently. Ideally, these should be run simultaneously, to help eliminate port overloading that might occur with separately optimized scheduling problems. The simultaneous running of the programs could provide insight into optimal ship scheduling problem, versus just the segmented POL tanker and container ships scheduling problems.

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## APPENDIX A. [ACRONYMS]

bbls: barrels, a measurement of liquid products

BUR: Bottom Up Review

BURU: Bottom Up Review - Update

cpu: Central Processing Unit

CJCS: Chairman, Joint Chiefs of Staff

DCNO: Deputy Chief of Naval Operations

DFM: Diesel Fuel Marine

DFSC: Defense Fuel Supply Center

DoD: Department of Defense

DoT: Department of Transportation

EUSC: Effective US Controlled

GAMS: General Algebraic Modeling System

ILA: Intratheater Lift Analysis

ILP: Integer Linear Programming

J4: Joint Staff's Director for Logistics

J4-MOB: Joint Staff Director for Logistics, Mobility Division

JP5: A kerosene based jet fuel used for US Navy aircraft

JP8: A kerosene based jet fuel, used for non-US Navy aircraft due to greater volatility

JS: Joint Staff

JSCP: Joint Strategic Capabilities Plan

LCAC: Landing Craft-Air Cushion

LP: Linear Program

MARAD: Maritime Administration

MAST: Methodology for Assigning Schedules to Tankers

mbbls: 1000's of bbls

MIDAS: Model for Intertheater Deployment by Air and Sea

MRS: Mobility Requirements Study

MRS BURU (MRS Bottom Up Review, Update)

MSC: Military Sealift Command

N4: DCNO for Logistics

NASSCO: National Steel and Shipbuilding Company

nm: Nautical Mile

NDRF: National Defense Reserve Fleet

OOTW: Operations Other Than War

OSD: Office of the Secretary of Defense

OSD(PA&E): Office of the Secretary of Defense Program Analysis and Evaluation

POL: Petroleum, Oil and Lubrication

ROS: Reduced Operating Status

RRF: Ready Reserve Force

SecTrans: Secretary of Transportation

SkedGen: The Schedule Generator

SPOD: Sea Port of Debarkation

SPOE: Sea Port of Embarkation

US: United States

USA: United States Army

USAF: United States Air Force

USMC: United States Marine Corps

USN: United States Navy

USTC: United States Transportation Command

# APPENDIX B. [DATA DESCRIPTION]

For ease of reading and consistency in this appendix, text in **bold print** represents pieces of data and variables in MAST.

## 1. Sea Ports of Debarkation (SPODs)

The data for the seven SPODs is summarized in Table 3. The ports are listed down the first column, with their characteristics across the top two rows. The **Name**, **Draft**, and **Number Berths** columns are straightforward (the draft information is drawn from *Lloyd's Ports of the World* [Lloyd's, 1996]). The **Pump Time** is conservatively estimated as the number of eight-hour days required to empty a 200,000 barrel tanker. **Buffer** and **InitPODInv** data is contained in the 'JP5Buf', 'JP8Buf', JP5Init' and 'JP8Init' columns. **Fuel Type** is either '8' for JP8 only, or 'b' for both (no port requires only JP5). Storage capacities of JP5 and JP8 (JP5Sto and JP8Sto) are in the last two columns, yielding **StoragePOD** data. The data derives from MRS BURU and DFSC (updated November, 1996).

***SPOD Data File***

| Name | Draft | Pump Time | Number Berths | JP5Buf (mbbls) | JP8Buf (mbbls) | JP5Init (mbbls) | JP8Init (mbbls) | Fuel Types | JP5Sto (mbbls) | JP8Sto (mbbls) |
|---|---|---|---|---|---|---|---|---|---|---|
| CAIRO | 38 | 3 | 4 | 0 | 72 | 0 | 0 | 8 | 0 | 714 |
| DGARCIA | 40 | 1 | 4 | 30 | 37 | 723 | 0 | b | 1,131 | 370 |
| GUAM | 36 | 1 | 3 | 0 | 137 | 0 | 1,000 | 8 | 0 | 1,900 |
| JAPAN | 40 | 3 | 2 | 0 | 130 | 0 | 661 | 8 | 0 | 3,906 |
| JEDDAH | 62 | 1 | 4 | 0 | 45 | 0 | 0 | 8 | 0 | 186 |
| KOREA | 36 | 1 | 2 | 0 | 459 | 0 | 2,324 | 8 | 0 | 1,904 |
| THAILAND | 40 | 1 | 6 | 0 | 32 | 0 | 0 | 8 | 0 | 320 |

**Table 3 -- SPOD Data.** The port **Name**, **Draft**, **Pump Time**, and **Number of Berths**, are as described above. 'JP5Buf', and 'JP8Buf' contain the data for the **Buffer** parameter (fuel reserves). **InitPODInv** gets its data from 'JP5Init' and 'JP8Init' (initial inventories). Fuels is as described above, and 'JP5Sto' and 'JP8Sto' are the values used by **StoragePOD** (storage capacities).

### 2. Sea Ports of Embarkation (SPOEs)

The data for the sixteen SPOEs is summarized in Table 4, similar in design to Table 3, with one exception. **FuelProd** data is contained in columns seven and eight, 'JP5Prod' and 'JP8Prod', and is measured in mbbls of daily production. The data derives from MRS BURU and DFSC (updated November, 1996).

***SPOE Data File***

| Name | Draft | Pump Time | Number Berths | Fuel Types | JP5Prod (mbbls) | JP8Prod (mbbls) | JP5Sto (mbbls) | JP8Sto (mbbls) |
|---|---|---|---|---|---|---|---|---|
| AL JUBAIL | 65 | 1 | 4 | 8 | 0 | 88 | 0 | 1,372 |
| AMUAY BAY | 40 | 1 | 4 | 8 | 0 | 52 | 0 | 100 |
| ANCHORAGE | 35 | 1 | 4 | 8 | 0 | 18 | 0 | 642 |
| CILACAP | 42 | 1 | 3 | 8 | 0 | 37 | 0 | 72 |
| FERNDALE | 36 | 1 | 1 | b | 43 | 0 | 875 | 498 |
| ITALY | 39 | 3 | 4 | 8 | 0 | 23 | 0 | 1,557 |
| LONGBEACH | 45 | 1 | 15 | 8 | 0 | 217 | 0 | 294 |
| NEW ORLEANS | 39 | 1 | 15 | 8 | 0 | 384 | 0 | 1,124 |
| OKINAWA | 40 | 1 | 2 | 8 | 0 | 28 | 0 | 878 |
| PEARL | 40 | 1 | 4 | 8 | 0 | 31 | 0 | 226 |
| PHILLY | 39 | 1 | 4 | 8 | 0 | 60 | 0 | 1,641 |
| PUERTORICO | 34 | 3 | 4 | 8 | 0 | 96 | 0 | 595 |
| PULAU BUKOM | 36 | 1 | 4 | 8 | 0 | 77 | 0 | 496 |
| ROTTERDAM | 41 | 1 | 10 | 8 | 0 | 65 | 0 | 3,747 |
| SPAIN | 66 | 1 | 2 | 8 | 0 | 72 | 0 | 2,354 |
| UK | 41 | 1 | 4 | 8 | 0 | 28 | 0 | 3,995 |

**Table 4 -- SPOE Data.** The port **Name** and **Draft, Pump Time** and **Number of Berths** are described above. The **Fuel Types** column indicates whether the port accommodates JP8 ('8') or both ('b') fuel types. The last two pairs of columns contain the amount of JP5 and JP8 production (**FuelProd**) and storage (**StoragePOD**).

### 3. Tankers

The data for the tankers is summarized in Table 5. A subset of the entire list of ships is provided (only 10 of the 92 are shown). MSC (MSC controlled tankers) and MARAD (all other tankers) provided the data on tanker characteristics, usage, and availability, via USTC.

***Tanker Data File***

| Ship Name | Draft | Speed | Capacity | ISPOE | IDelay | SType | SClass |
|---|---|---|---|---|---|---|---|
| JURONG | 20 | 12 | 36 | PHILLY | 14 | Sh Dr | EUSC |
| PAGODA | 34 | 14 | 275 | AMUAYBAY | 13 | Med | EUSC |
| DANUBE | 36 | 14 | 197 | AMUAYBAY | 15 | HST | EUSC |
| R HAL DEAN | 40 | 14 | 600 | PEARL | 13 | Large | EUSC |
| SAMUEL L COBB | 36 | 16 | 239 | LONGBEACH | 17 | Med | MSC |
| MISSION CAPISTRANO | 36 | 17 | 303 | NEWORLEANS | 24 | Med | RRF |
| RANGER | 33 | 16 | 308 | AMUAYBAY | 17 | Med | USFLAG |
| PHILADELPHIA SUN | 33 | 16 | 233 | LONGBEACH | 22 | HST | USFLAG |
| PROJ TANKER # 7 | 37 | 15 | 350 | LONGBEACH | 14 | Large | USFLAG |
| OVERSEAS OHIO | 49 | 16 | 667 | SPAIN | 18 | Large | USFLAG |

**Table 5** -- Tanker Data (a subset). The ship name, draft, speed, and capacity are straight forward. The **ISPOE** is the initial SPOE for onloading fuel. The **IDelay** is the first day the tanker can get to the SPOE ready to onload fuel. The **SType** and **SClass** are the ship type and the ship class. ***PROJECTED TANKER*** *#7* is one of the fifteen vessels expected to be in service in 2003 that has yet to be funded.

## 4. Fuel Requirements

Table 6 summarizes fuel requirements (only a few lines are shown). The POL requirements, 13,518 mbbls over the 75-day window, derive from the Intratheater Lift Analysis (ILA) study (USA, USAF, and USMC requirements) and from the MRS (USN requirements). The requirements are specified by port, day, and fuel type. *The POL requirements used in this thesis are notional.*

***Fuel Requirements File***

| Name | Fuel Type | Day | Rqmt (Mbbls) |
|---|---|---|---|
| CAIRO | JP8 | 46 | 54 |
| DGARCIA | JP5 | 51 | 47 |
| DGARCIA | JP8 | 57 | 48 |
| GUAM | JP8 | 30 | 51 |

**Table 6** -- The data accounts for every port, fuel type, and day combination. Only a few lines are shown (one for each port and fuel type). The actual file consists of hundreds of lines, and the fuel requirements total 13,518 mbbls over the 75-day window.

### 5. Distance Table

The distance data (Table 7) derives from an algorithm for computing the distances between ports within the MIDAS model. The distance table assumes both canals (Suez and Panama) are open and transit remains unimpeded.

***Distance Data File***

| DISTANCE | CAIRO | DGARCIA | GUAM | JAPAN | JEDDAH | KOREA | THAILAND |
|---|---|---|---|---|---|---|---|
| AL JUBAIL | 3,228 | 2,811 | 7,439 | 6,797 | 2,619 | 6,356 | 4,601 |
| AMUAY BAY | 5,900 | 9,352 | 9,836 | 8,538 | 6,727 | 8,929 | 11,496 |
| ANCHORAGE | 11,343 | 8,694 | 4,644 | 3,386 | 10,734 | 3,737 | 6,304 |
| CILACAP | 5,624 | 2,370 | 4,407 | 3,591 | 5,015 | 3,324 | 1,916 |
| FERNDALE | 10,502 | 9,606 | 5,556 | 4,298 | 11,329 | 4,649 | 7,216 |
| ITALY | 1,066 | 4,557 | 9,755 | 9,113 | 1,893 | 8,672 | 6,917 |
| LONG BEACH | 9,306 | 10,112 | 6,201 | 4,903 | 10,133 | 5,296 | 7,863 |
| NEWORLEANS | 6,490 | 9,981 | 10,503 | 9,205 | 7,317 | 9,596 | 12,163 |
| OKINAWA | 7,314 | 4,609 | 1,805 | 885 | 6,705 | 722 | 2,275 |
| PULAU BUKOM | 5,076 | 2,427 | 3,659 | 3,017 | 4,467 | 2,576 | 821 |
| PEARL | 11,035 | 8,307 | 5,087 | 3,439 | 10,436 | 4,039 | 6,157 |
| PHILADELPHIA | 5,337 | 8,828 | 11,069 | 9,771 | 6,164 | 10,162 | 11,188 |
| PUERTO RICO | 5,439 | 8,930 | 10,061 | 8,763 | 6,266 | 9,154 | 11,290 |

**Table 7 -- Distance Table.** The distance data is organized with the SPOEs down the first column, and the SPODs on the first row. Distances are in nautical miles.

### *Merged Tanker Data*

| Ship Name | Draft | Speed | Capacity | ISPOE | IDelay | SType | SClass | Number in Group |
|---|---|---|---|---|---|---|---|---|
| JURONG | 20 | 12 | 36 | PHILLY | 14 | Sh Dr | EUSC | 1 |
| PAGODA | 34 | 14 | 275 | AMUAYBAY | 13 | Med | EUSC | 3 |
| DANUBE | 36 | 14 | 197 | AMUAYBAY | 15 | HST | EUSC | 2 |
| R HAL DEAN | 40 | 14 | 600 | PEARL | 13 | Large | EUSC | 2 |
| VEGA | 40 | 14 | 296 | PEARL | 15 | Med | EUSC | 4 |
| COLORADO | 42 | 15 | 648 | UK | 14 | Large | EUSC | 1 |
| LUCY | 44 | 15 | 457 | SPAIN | 11 | Large | EUSC | 4 |
| BERYL | 45 | 14 | 666 | LONGBEACH | 7 | Large | EUSC | 8 |
| ELBE | 62 | 15 | 455 | SPAIN | 9 | Large | EUSC | 1 |
| HANK | 23 | 14 | 48 | PULAUBUKOM | 5 | Sh Dr | MSC | 2 |
| KEN | 31 | 13 | 142 | OKINAWA | 7 | Sm | MSC | 3 |
| SAMUEL L COBB | 36 | 16 | 239 | LONGBEACH | 17 | Med | MSC | 3 |
| GUS W DARNELL | 36 | 16 | 239 | PEARL | 14 | Med | MSC | 3 |
| MISSION CAPISTRANO | 36 | 17 | 303 | NEWORLEANS | 24 | Med | RRF | 2 |
| NODAWAY | 16 | 10 | 31 | OKINAWA | 11 | Sh Dr | TT | 3 |
| RANGER | 33 | 16 | 308 | AMUAYBAY | 17 | Med | USFLAG | 8 |
| PHILADELPHIA SUN | 33 | 16 | 233 | LONGBEACH | 22 | HST | USFLAG | 2 |
| MORSKY | 35 | 16 | 283 | LONGBEACH | 26 | Med | USFLAG | 2 |
| FALCON LEADER | 36 | 16 | 226 | PHILLY | 23 | HST | USFLAG | 1 |
| MONSEIGNEUR SPRAY | 37 | 16 | 275 | NEWORLEANS | 22 | Med | USFLAG | 3 |
| PTSEVEN | 37 | 15 | 350 | LONGBEACH | 14 | Large | USFLAG | 17 |
| CHEVRON WASHINGTON | 37 | 15 | 269 | NEWORLEANS | 22 | Med | USFLAG | 5 |
| JULIUS HAMMER | 39 | 16 | 300 | NEWORLEANS | 21 | Med | USFLAG | 3 |
| CHESAPEAKE TRADER | 40 | 15 | 359 | LONGBEACH | 12 | Large | USFLAG | 3 |
| S/R CHARLESTON | 42 | 17 | 373 | LONGBEACH | 9 | Large | USFLAG | 3 |
| PHILADELPHIA | 49 | 15 | 350 | SPAIN | 12 | Large | USFLAG | 6 |

**Table 8** -- The 92 tankers are aggregated to reduce the size of the problem, yet still maintain a close semblance of the feasible set of schedules. For the twelve projected tankers, Projected Tanker (PT) Seven represents the schedules of the group. The number of schedules, is reduced from over 798,000 to 289,661.

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